IMPROVING BSFC THROUGH MULTIPLE INJECTIONS AND VARYING CETANE NUMBER FOR A LIGHT DUTY DIESEL ENGINE

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Improving BSFC through Multiple Injections and Varying Cetane Number for a Light Duty Diesel Engine

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Due to their relatively low carbon dioxide emissions and superior fuel efficiency performance, interest in further utilization of diesel engines for commercial and industrial use continues to grow. The concept of multiple injections provides ever further optimization of the diesel engine in terms of improving emissions, combustion noise, and combustion efficiencies. With the development of highly efficient diesel aftertreatment systems, the need for in-cylinder control of harmful emissions has been significantly reduced. This adaptation lifts the emissions barrier to maximizing combustion efficiency through multiple injections. This study serves to reexamine multiple injection capabilities in improving combustion characteristics, specifically targeting brake specific fuel consumption, without the constraint of reducing emissions through in cylinder means. Tests will be conducted on a John Deere 4.5L 4 cylinder medium-duty industrial diesel engine. A test matrix sweeping injection duration & timing will act as the main data points. Pilot injection, a secondary injection occurring a few degrees prior to the main event, will serve as the additional injection component. As another layer to the study, two fuels with varying cetane numbers will each be utilized in the study to better understand the effect of cetane number on multiple injection event. From these tests, data should yield a strong base from which to analyze peak injection schedules to improve the operating conditions of diesel engines.

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NOMENCLATURE

BSFC: Brake Specific Fuel Consumption

CN: Cetane Number

MFB: Mass Fraction Burned

EGR: Exhaust Gas Recirculation

TDC: Top Dead Center

BTDC: Before Top Dead Center

IMEP: Indicated Mean Effective Pressure

DAQ: Data Acquisition System

ROHR: Rate of Heat Release

CHAPTER I

INTRODUCTION

Over the past several years, industry interest in diesel engines for their low carbon dioxide footprint, higher efficiencies, and long term reliability when compared to gasoline engines has spurred continued research to further these inherent benefits [Hansen]. Diesel engine customers of today are looking for a long lasting product that obtains ever higher fuel efficiencies - all within the constraints of emission regulations. Emission regulations introduced by the Environmental Protection Agency aim to prevent harmful gases produced by internal combustion engines from creating a negative health impact, whether directly or indirectly, on the citizens of the United States. One possible solution to all these requirements is the use of multiple injections per cycle, as opposed to the single injection event used since the advent of the internal combustion engine. This topic has seen a fairly robust volume of research over the last two decades, and certain aspects of multiple injection are relatively well understood, especially when considering the benefits of close-coupled pilot and post injections [Barman, Biswas, Hardy, Mallamo]. However, most of these studies were conducted under the lens of emissions control, rather than performance improvements. With the invention - and as of now implementation [Sanchez] - of new diesel aftertreatment technology, the need for in-cylinder emissions control has been greatly reduced, rendering much of the prior research relatively obsolete. As opposed to the large body of work done on general multiple injection studies, the effect of varying cetane number on the input fuel on multiple injection characteristics is fairly understudied [Allocca, Chen]. This research parameter could shed light on how cetane number could affect dwell periods necessary to achieve expected multiple injection results [Barman, Biswas, Hardy, Mallamo]. In this study, the aim is to improve BSFC by testing multiple injection points regardless of emission effects across 2 fuels of varying cetane number.

Literature Review

Basis of Multiple Injections

The concept behind multiple injection has been around since the 1960's, however the primary barrier to implementation resulted from insufficient injector technology. In order for injectors to keep up with the demand of multiple injections per cycle, significantly higher pressure capabilities and control was necessary, along with time control within the microsecond range to even define an injection schedule. Later in the 1990's, injector technology such as common rail injection systems, when coupled with electronic control units, were advanced enough to make multiple injections a reality. However, pressure requirements and fine injector schedule maintenance can still be an issue today.

Types of Injections

When discussing multiple injections, it is important to coordinate terminology with the specific injector schedule under consideration. For example, dwell refers to the time between the end of one injection event and the start of another one. There are four primary styles of injections (other than the main injection): pre, post, after, early, and split.

- Pre Injection. Occurs prior to the main injection. As opposed to an early injection, the dwell in-between the primary injection event is relatively small.
- Post Injection. Similarly to the pre injection, the post injection occurs after the main injection event, also with a small dwell between the main and post injection.
- After Injection. Occurs very late in terms of dwell time as opposed to post injection.

- Early Injection. Similar to after injection, the dwell time between is very large prior to the main injection.
- Split Injection. A much more loosely defined term, most notably differing in the amount of fuel injected as opposed to the other 4 multiple injection definitions. Here, the amount of fuel in the secondary injection is more than 20%, and can be as much as 50%. At that point, the differentiation between what is the primary and secondary injection tends to grey.

Split Injections

When compared to the other styles of injections, split injections lack the most understanding and in-depth study. Simply based on the loose definition of what defines the split injection schedule places so many additional variables and possible testing points that fully understanding the many possibilities of split injections is more challenging than the other styles of multiple injections. For example, the fuel amount per injection pulse from 20% to 80% of total fuel along with any range of dwell times in between those pulses are all under the realm of split injections. Due to this, literature is usually only able to capture a small window of these many possibilities, although combustion models and optimization functions have been used to reduce the window of potential test schedules. Some significant results of utilizing split injections involve modulating the rate of heat release and increasing the mixing inside the chamber [Anselmi, Borz, Koci]. By splitting the total injected quantity into two (or more) events, the rate of heat release can be reduced by increasing the overall combustion time and decreasing the amount of combustible material available at one time. This is especially apparent using split injection, as more significant portions of the total amount of fuel are combusted at separate times. Increased mixing inside the chamber is achieved by the further jet penetration of the 2nd

injected quantity, along with the turbulent mixing created when the 2nd injection meets the partially combusted 1st injection [Koci]. This allows intermediate compounds (such as unburned hydrocarbons or CO) to reach a more complete stage of combustion, ending in relatively harmless carbon dioxide and water. However, this turbulent mixing effect of increased jet penetration and more complete combustion only occurred at several "sweet spots" across the range of potential injection times, as some papers were unable to find this phenomenon at all [Morgan, Borz]. From these two modifications in the combustion chamber, reductions in HC, CO, and PM along with thermal efficiency benefits can all be observed [Swami]. These results show a promising correlation between the use of split injections, which reduce PM, and the utilization of EGR, which has a significant NOx/PM tradeoff [Mobasheri, Zhang]. Another study found a reduction in combustion noise with roughly equal injection quantities at a relatively small dwell time [Morgan]. Ultimately, the primary issue with split injection is that the benefits observed from its use are less profound than the benefits observed from other multiple injection strategies (pre, post, etc.). While additional work may provide new information about the topic, currently split injections is not the preferred technical for increasing combustion efficiencies, reducing fuel consumption, or reducing emissions output.

Pilot Injections

Pilot injection schedules, defined as an injection occurring prior to the main injection and involving less than 20% of the total injected fuel, have received fairly extensive study and some common trends are beginning to emerge. One of the most important utilization of pilot injections involve control over the ignition delay [Biswas]. By introducing a small fraction of the fuel prior to the main charge, the in-cylinder conditions are more conducive to combustion once the primary injection occurs. A smaller charge given additional time to mix and combust makes the time required for combustion of the main injections drop significantly. At the same time, a more gradual combustion process over the course of two combustions reduces the peak in-cylinder pressure and temperature. This provides emission benefits, but more significantly the combustion noise drops to much more bearable levels, especially at low to medium loads. Also at higher pilot duration and dwell time, noticeable BSFC and torque improvements occur [Barman]. More so than the other forms of injection, pilot events are much more susceptible to changing performance based on fuel properties. Factors such as viscosity, aromatic content, and cetane number all have effects on the performance of pilot injections, ranging from decreasing commanded fuel injected to altering the control over ignition delay [Allocca, Chen].

Post Injections

As stated above, post injections are defined as an additional injection following the main injection consisting of less than 20% of the total injected fuel. One of the most significant utilizations of post injections is the reduction of smoke emissions. The reasons behind this phenomenon seem to be both fluidic and thermal in nature [O'Connor 2]. In terms of their thermal contributions, reducing the amount of fuel injected at one time allows for lower peak temperatures (typically under 2000 Kelvin) which inhibits the formation of radical particles such as NOx [Osada]. Decreasing the overall temperature increases the length of combustion, allowing more time for unburned charge - the main culprit behind UHC and PM emissions - to be ignited and oxidized to less harmful gases [Mallamo]. In terms of the fluidic contributions, increased turbulence inside the combustion chamber following a second injection burst allows for more complete mixing [Molina]. Similarly, unburned charge from the initial injection ignites during the second combustion event. When looking at how long of a dwell time to use between the two injections, separate benefits are achieved between using a shorter dwell time and a longer dwell time. With a close-coupled dwell time, soot reductions are observed along with benefits to fuel efficiency, but with increased NOx emissions. Here, the specific timing is important; this benefits occur at a specific “sweet spot”. With a longer dwell time, more significant soot reductions are observed with relatively no benefit to fuel efficiency and increased hydrocarbon emissions. As opposed to the close coupled injection, the quantity of fuel injected is more critical than the timing to observe these benefits [Martin, Barman]. Similarly with split injections, the benefits observed from reducing smoke emissions allows for higher tolerances of EGR, simultaneously reducing NOx emissions [Hardy]. Increasing the injections pressure aids in enhancing the benefits observed with utilizing post injections, but this does come at a limit. At very upper limits of most common rail injection systems today, pressure waves from the main injection can interfere with the completion of the post injection, possibly stopping it all together [Henein].

CHAPTER II

EXPERIMENTAL SETUP & TESTING REGIME

Engine Description

Multiple Injection tests will be run on a 4 cylinder 4.5 liter John Deere diesel automotive engine. These engines run primarily as a stationary engine for agricultural field work. The engine is turbocharged with exhaust gas recirculation (EGR) functions. A dynamometer is connected to the engine crankshaft to apply load and record corresponding output torque. A summary of engine parameters are listed in table 1 and a picture of the engine is displayed in figure 1.

Table 1: Description of engine parameters utilized in multiple injection study.

Number of cylinders	4
Displacement Volume	4.5 L
Maximum Power	165 - 180 hp @ 2000-2200 rpm
Maximum Torque	645 N*m @ 1400 rpm
Compression Ratio	17.0:1
Bore	106 mm
Stroke	127 mm
Fuel Injection System	Electronic Controller Rotary Injection

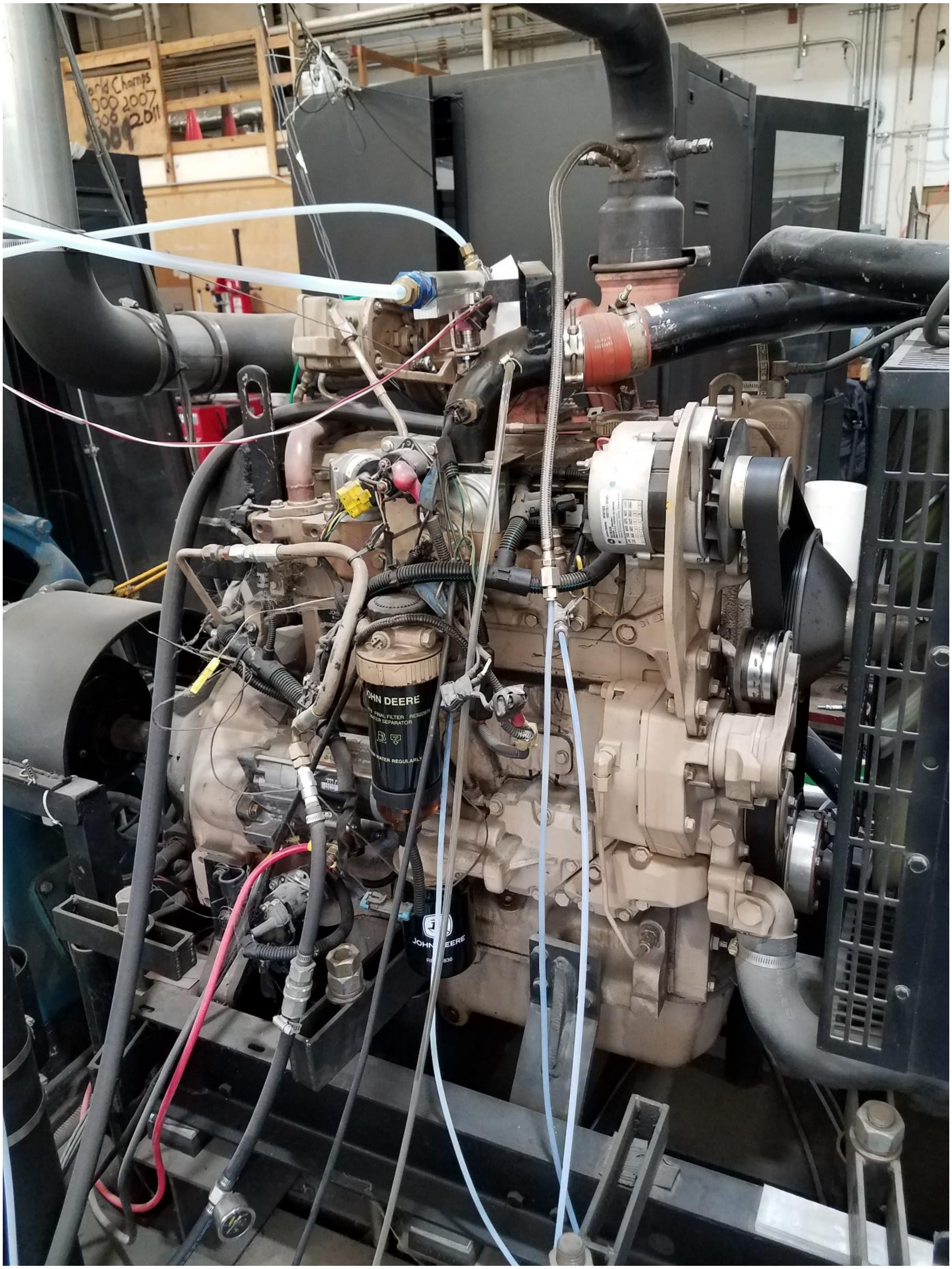

Figure 1: Image of 4.5l John Deere diesel engine, the basis for the tests performed in this study.

Data Acquisition Systems

Numerous instruments, devices, and programs are utilized to record phenomenon produced inside the engine. Measurement devices include dozens of thermocouples for everything from exhaust to coolant temperature, in-cylinder pressure sensors, an encoder for crank angle measurement, among other pieces of equipment. A MEXA-7100D Horiba emissions bench records CO_2, NO_x, unburned HCs, and CO. Figure 2 shows the interface with the emissions bench. An in-house mini-dilution tunnel & smoke meter collects particulate matter data.

Figure 2: Interface with the MEXA emission bench, responsible for taking all emission data other than the particulate matter data.

Pressure, temperature, and crank angle data are funneled through a National Instruments data acquisition system (DAQ) which is compiled and displayed on a CalVIEW program, where engine parameters such as injection timing, number of injection, and other operating procedures are controlled. Figure 3 shows the interface with the CalVIEW control system. When data is ready to be taken, a brief screen shot of several hundred crank angles are compiled into an output excel document with all the necessary raw data (emissions, temperature, pressure, IMEP, etc.).

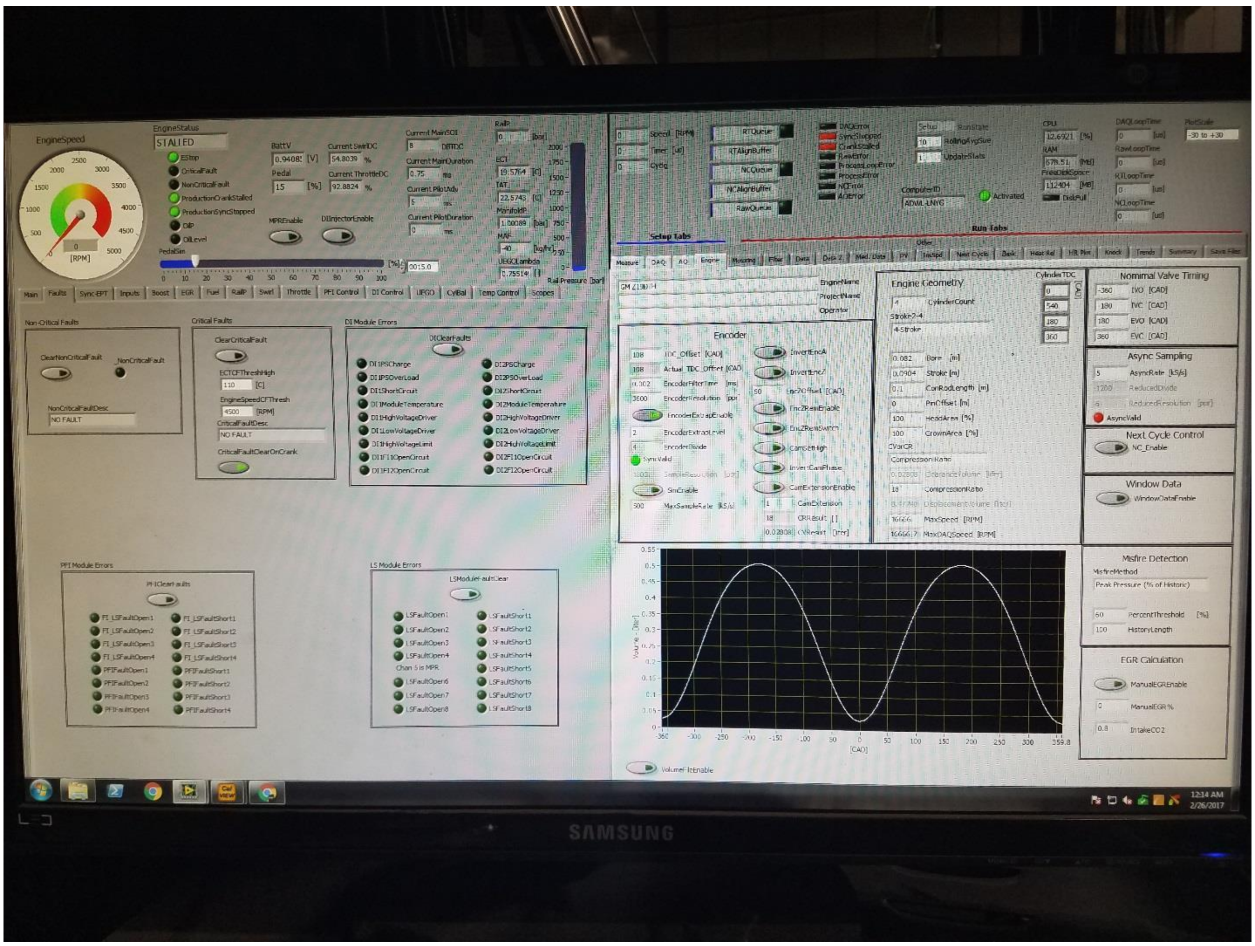

Figure 3: Control panel used to run the engine during operation. Allows for real-time viewing of in-cylinder pressure data along with other important characteristics.

Testing Schedule

The testing schedule will focus on the effects of pilot injections. For the scope of this project, a total of 3 separate testing condition: pilot injection timing, load condition, and 2 separate fuels of varying cetane number provided by Shell, Inc. Table 2 quantifies the specifics of the test matrix:

Table 2: Description of the pilot injection testing schedule.

Light Load (2.22 bar)			Medium Load (5.55 bar)		
Pilot Timing (BTDC)	Main Timing (BTDC)	Pilot Quantity (% total fuel)	Pilot Timing (BTDC)	Main Timing (BTDC)	Pilot Quantity (% total fuel)
12	9	20	12	9	20
15	9	20	15	9	20

In total, this is 8 separate engine conditions for taking data. If additional time and resources were available, a larger test matrix would've been undertaken. Finally, table 3 describes the fuel properties of the two types of diesel fuel utilized in the project:

Table 3: Overview of the properties of the two fuels utilized in the study.

Fuel	Cetane Number	Aromatic Content (%)	90% Distillation Temperature (°C)
1	30	20	270
2	55	20	270

CHAPTER III

RESULTS

Brake Fuel Conversion Efficiency

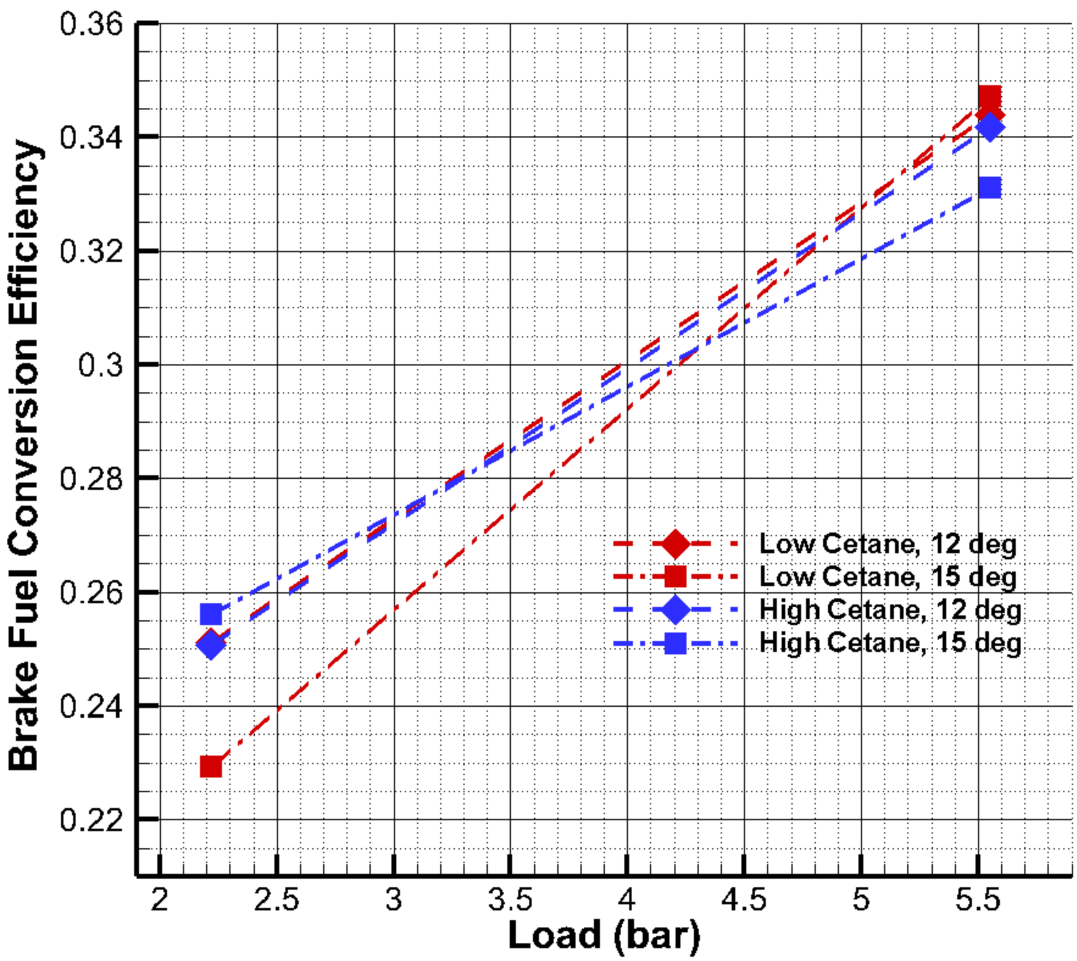

Figure 4: Brake fuel conversion efficiency for each fuel & pilot injection conditions as a function of load.

To compare the value of BSFC per load case on a normalized basis, the brake fuel conversion efficiency was utilized to compare each fuel, injection case, and load on a similar basis. Fuel conversion efficiency is the inverse product of BSFC and the heating value of the fuel. Figure 4 shows the results of the fuel conversion efficiency across every studied case. Although the general trend for each fuel & injection condition are similar, some interesting differences of several percent is present between various cases. The rest of the results will examine the combustion characteristics of each case and extract understanding of the fuel conversion efficiency of results from the in-cylinder combustion events.

Rate of Heat Release

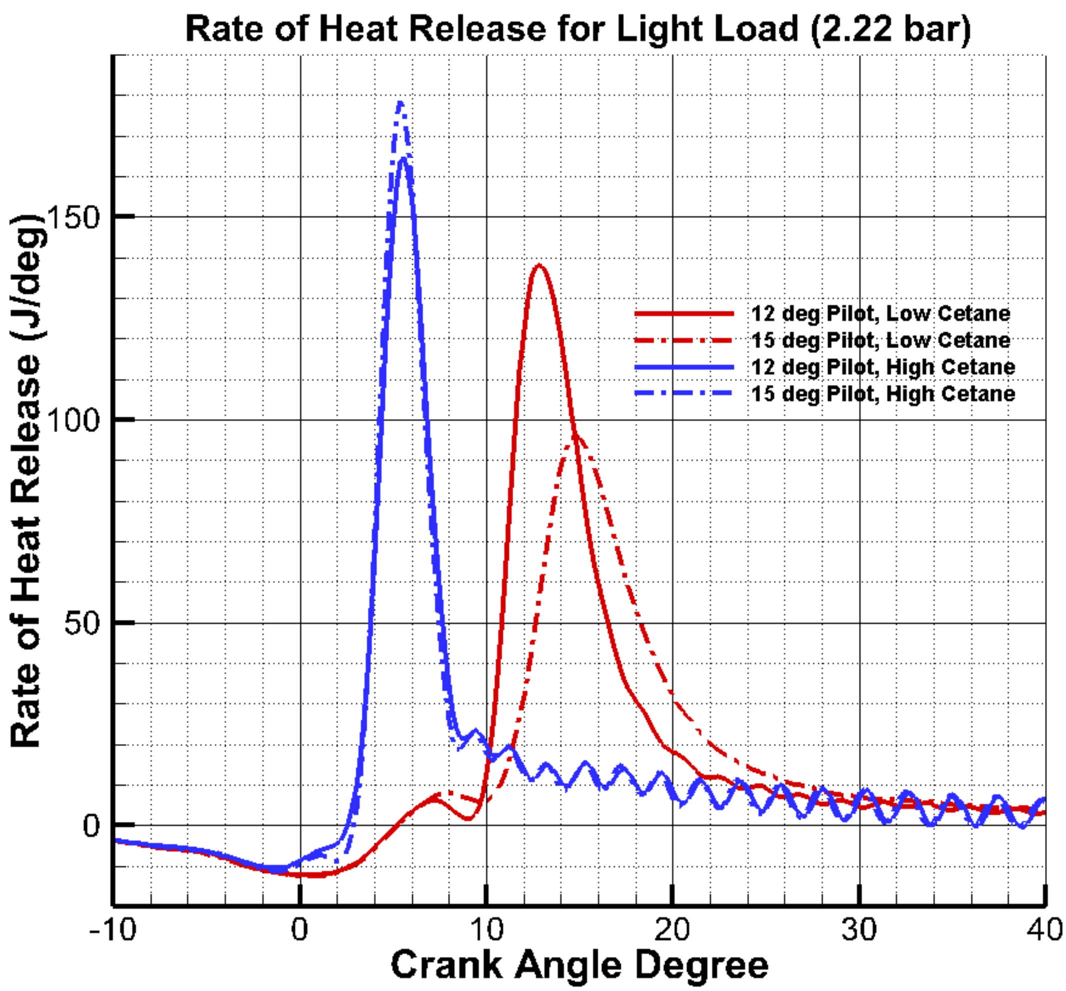

Figure 5: ROHR versus CAD curves for each fuel and pilot injection condition for the light load (2.22 bar) condition.

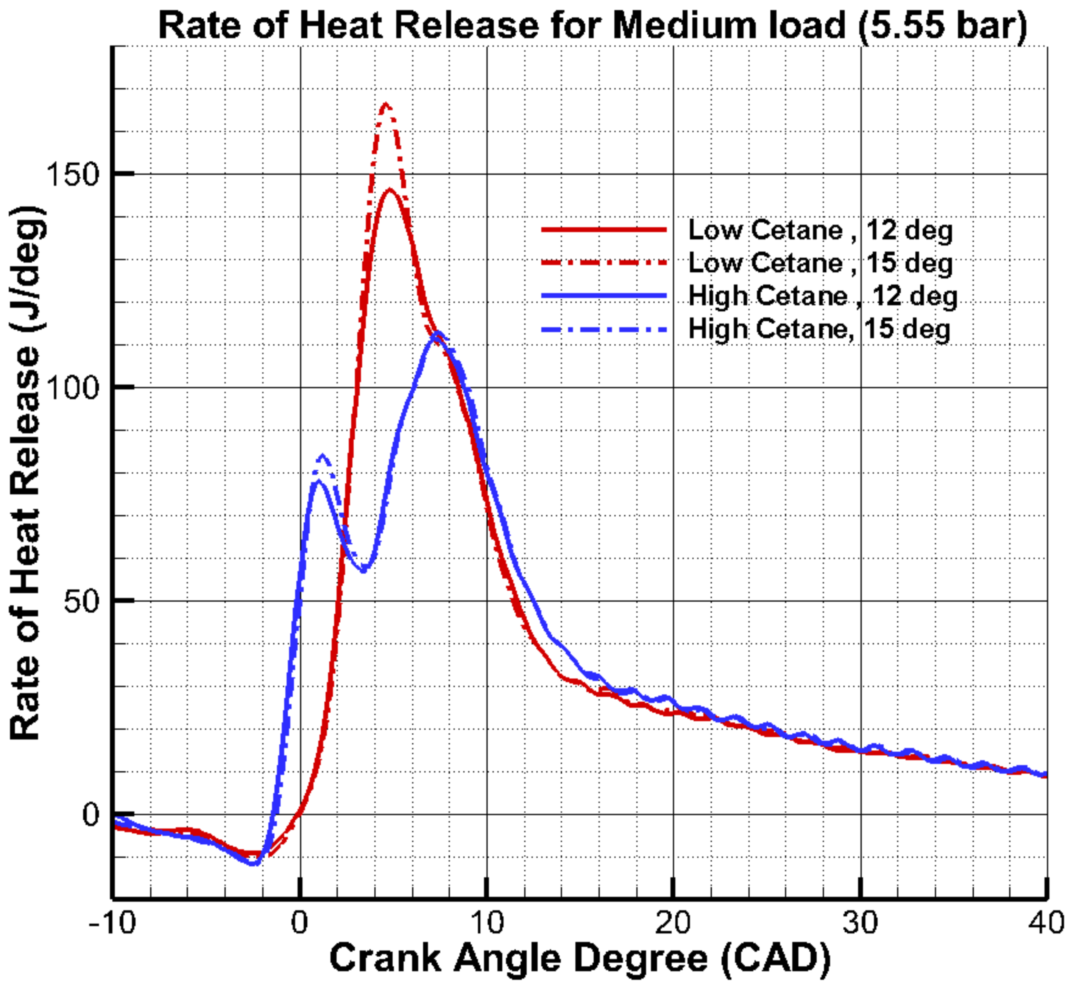

Figure 6: ROHR versus CAD curves for each fuel and pilot condition for the medium load (5.55 bar) condition.

In figures 5 & 6, rate of heat release (ROHR) curves gives insight into the combustion conditions occurring inside the cylinder, where zero degrees describes TDC. From the rate of heat release curves, information regarding various combustion phenomenon caused by each fuel and injection condition can be more easily examined.

The pilot injection has a very clear and present mark at the low load condition, especially for the low cetane fuel. The smaller rise in ROHR occurring 4-6 degrees prior to the dramatic heat release increase is the effect of the pilot injection. For the high cetane fuel, the effect is less noticeable, but an appreciable rise in ROHR does occur prior to the main combustion event. When considering medium load, the presence of the prior ROHR increase due to a pilot injection is imperceptible. However, some less obvious changes due to the pilot injection occur. Nowhere is this more obvious than in the comparison between the 15 degree low cetane cases for each load condition. During the low load case, the ROHR of the low cetane 15 degree case is highly stunted, almost 50 [J/deg] behind the other low cetane case. However when looking at the medium load figure, that same operating condition increases by 65 [J/deg], even surpassing the low cetane 12 degree case. Clearly, the pilot injection does have an effect on combustion parameters simply by the amount of increase of the ROHR curves.

When considering the cetane number of the fuel, very obvious differences between the high cetane (blue) and low cetane (red) curves are apparent. For the light load case, the curves show relatively similar trends, but the main combustion occurs at different times. Also, the higher cetane fuel is able to achieve a higher peak ROHR, implying higher in-cylinder temperatures and pressures at that peak. These higher gas conditions certainly show off the higher combustibility of the fuel. Much more significant differences in curve shape occur at the medium load, however. The low cetane fuel exhibits a similar overall trend at the medium load as at the low load, however the peak ROHR increased for both fuels when brought to higher load. The medium load high cetane case, on the other hand, has a completely different curve shape between the two loads. At medium load, the high cetane fuel exhibits a dual stage combustion indicative of the combustibility of the fuel. During the main injection event, the first wave of fuel that enters the cylinder penetrates through the present air, makes contact with the turbulent-inducing cylinder head, and mixes well with the surrounding air. This pre-mixed fuel reaches combustion first; all of this occurring while the later stage injected fuel is mixing with the air closer to the injector. However, the fuel & air near the injector is not well enough mixed to reach ignition once the flame front from the initial combustion reaches the injector side of the cylinder. Thus, two distinct combustion events occur: the rapid, initial combustion of the premixed fuel near the cylinder head and the diffusion combustion occurring later near the injector. This can only occur with a fuel that is sensitive to combustion conditions; otherwise higher in-cylinder temperatures and pressures are necessary to combust the fuel. This is why the dual stage combustion is only present in the high cetane fuel.

Ignition Delay

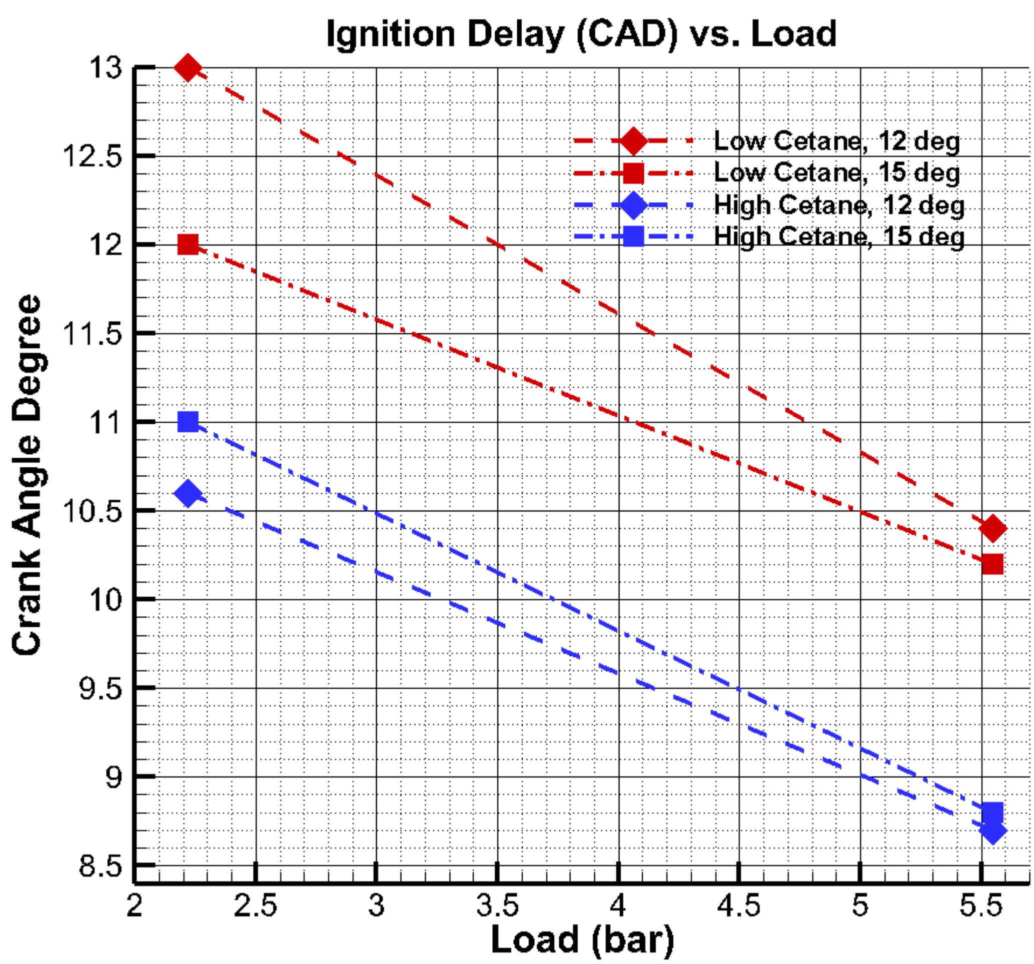

Figure 7: Ignition delay for each fuel & injection parameter as a function of load.

Another combustion parameter visible in the ROHR curves is the delay between the main commanded injection and the start of the main combustion event. In terms of real engine data, ignition delay is defined as the number of degrees between the set injection point - from table 2, this value is 9 degrees - and the first point of positive heat release. Figure 7 displays the ignition delay for all eight testing conditions, where blue defines the higher cetane fuel and red is the lower cetane fuel.

Unsurprisingly, the fuel of higher cetane number, and therefore higher combustibility, has a shorter ignition delay than the lower cetane fuel. The difference at its most extreme is a 3 degree difference, or roughly 25% faster than the lower cetane fuel. This is fairly significant - faster combustion achieves higher in-cylinder pressure and temperature which correlates to the greater peaks of heat release as seen in figure 5. In this respect, the faster combustion seems to correlate to a higher fuel conversion efficiency. When considering the low load condition, the higher cetane fuel has the shortest combustion duration and subsequently produces higher efficiencies. At the medium load condition, the dual stage combustion of the high cetane fuel correlates to a slower combustion duration and consequently the lower cetane number fuel produces higher fuel conversion efficiency.

Another interesting result from ignition delay is the inconsistency between the 12 and 15 degree injection conditions between the two fuels. While the 15 degree injection condition produces a faster response in the lower cetane fuel, it has the opposite effect in the high cetane fuel. When considering the lower cetane fuel, the additional time given to create a more complete mixture between fuel and air in the 15 degree injection condition would intuitively aid in accelerating combustion, as is seen in the results. However, this is not true for the higher cetane fuel. The higher pressures and temperatures as the cylinder approaches TDC seem to favor a later injection, making the 12 degree injection more heavily impact the injection delay as it is introduced in a more combustion friendly environment. That is where the higher combustibility of the 55 CN fuel plays a counterintuitive role in combustion results. Another result that agrees with the ROHR results is the essential elimination of the impact that the pilot injection has on injection delay at medium load. Although fairly high differences exist at the low load condition, that difference decreases to less than 0.2 degrees between each fuel's injection conditions. This agrees with the medium load ROHR curves seen in figure 6, where the effect of the pilot injection is imperceptible.

Mass Fraction Burned

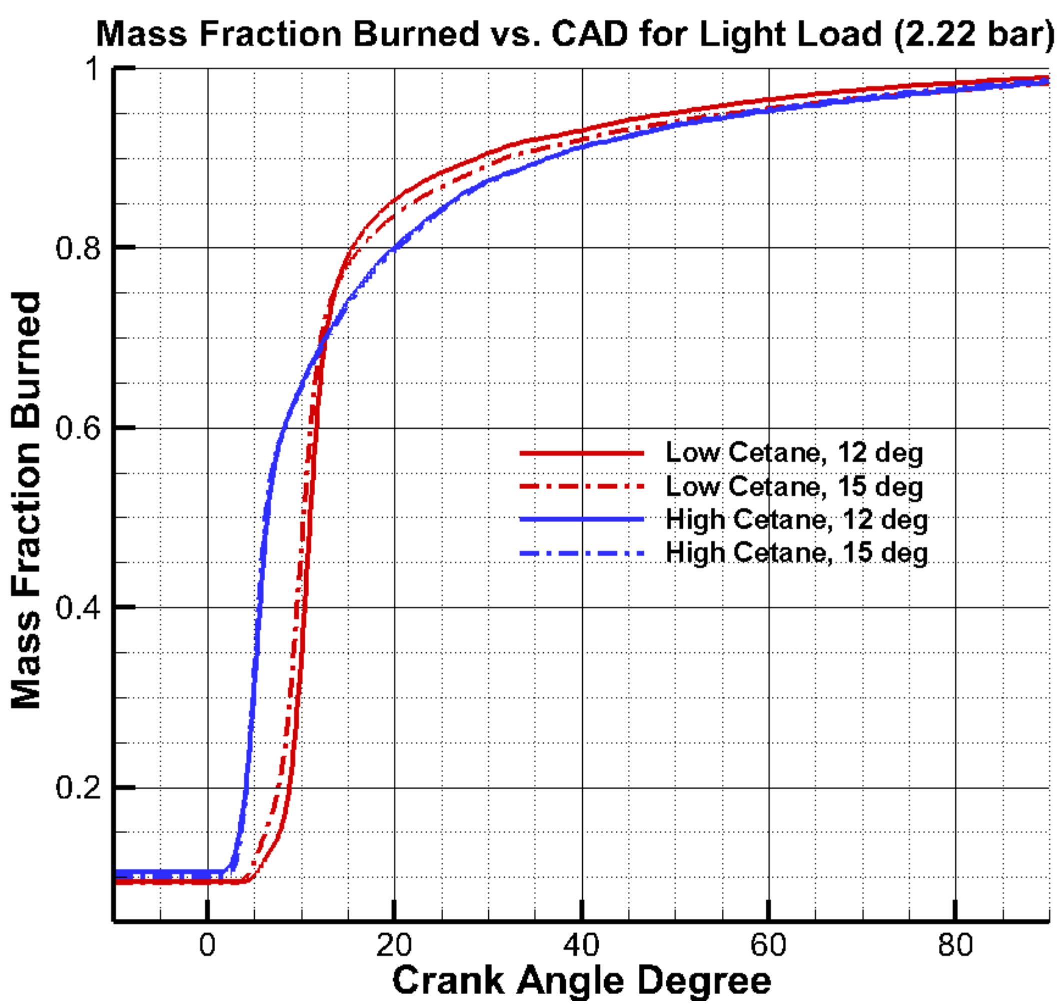

Figure 8: Mass fraction of fuel burned as a function of CAD for each fuel & injection condition.

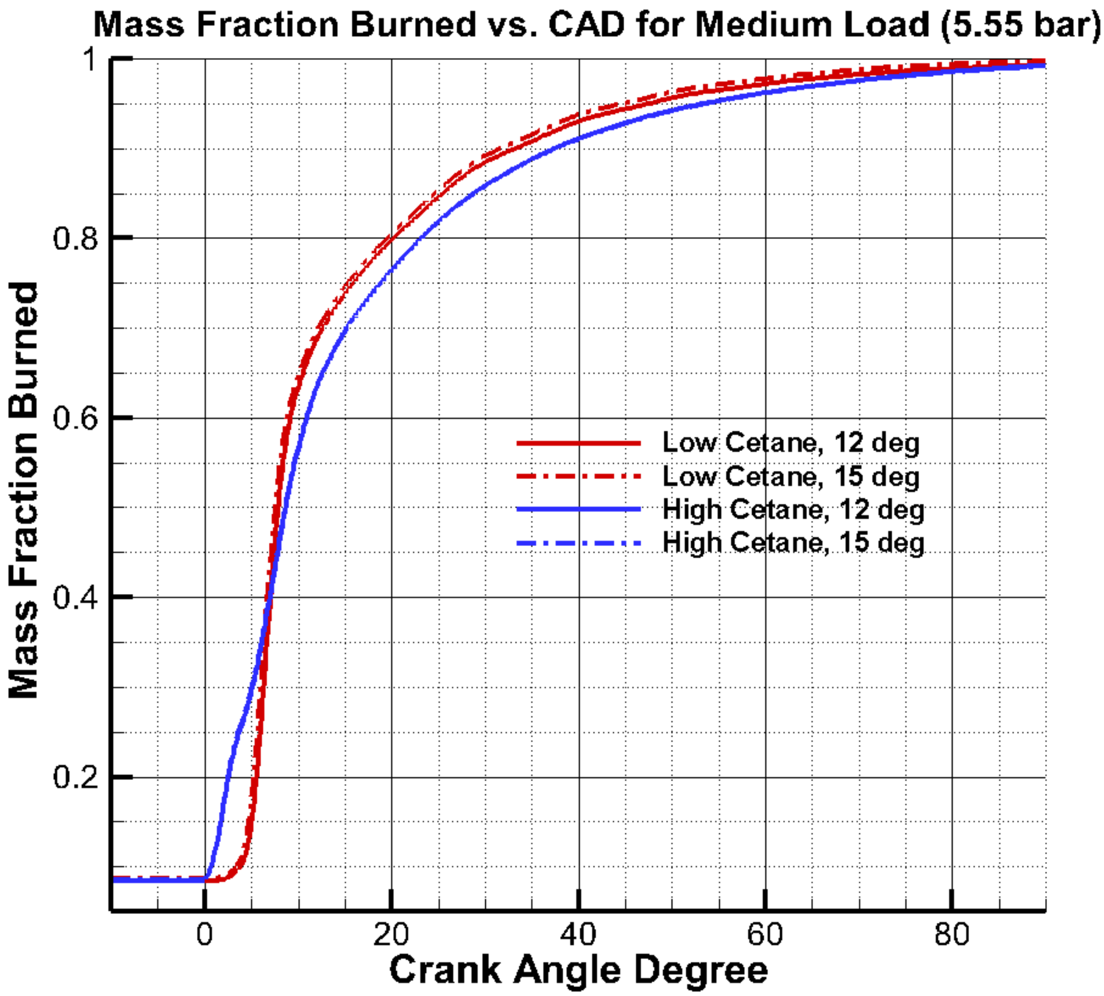

Figure 9: Mass fraction of fuel burned as a function of CAD for each fuel & injection condition at medium load.

In many ways, the MFB curves shown in figures 8 & 9 follow similar trends described in the ROHR curves back in figure 5 & 6. At the low load condition, the high cetane number case exhibits little change between the two injection cases, while the low cetane number curves have fairly different characteristics. This agrees with the results of the ROHR curves, where the low cetane number curve had highly visible rises in local heat release prior to the main combustion event. Similarly, the medium load curves for each fuel are nearly identical - correlating to the imperceptibility of the pilot injection in the medium load ROHR curves.

In figure 9, the MFB curve of the high cetane fuel has a fairly odd shape as compared to the other load & fuel curves. Rather than having an initial jump between 0.5 - 1% signifying the start of primary combustion, the curve has a more gradual increase up to about 25% of the total fuel combusted before reaching that primary combustion shape. Recalling back to figure 6, this is likely due to the dual-stage combustion exhibited by the higher cetane fuel at medium load. However, an argument could be made that the pilot injection exaggerates this combustion phenomenon, especially when considering the fraction of fuel that combusts prior to the primary event is very close to the fraction injected during the pilot injection (20% of the total fuel). Some combination of these two effects is likely the cause for this more gradual phenomenon. As seen in the previous example with ignition delay, a faster combustion seems to correlate to a higher fuel conversion efficiency, which seems to be consistent with the analysis of this oddly shaped MFB curve. Both injection conditions at medium load and high CN fuel drop below their low CN relatives in terms of fuel conversion efficiency, and this slow initial combustion seen in the MFB figure could be the reason for that.

CHAPTER IV

CONCLUSION

At least in terms of the multiple injections, perhaps the most significant conclusion of this paper is the lack of effect at a higher load. Figures for medium load of the rate of heat release, ignition delay, and mass fraction burned all seem to agree on the little effect that pilot injection had on these conditions. This may be more of a comment on the small scale of the test schedule, as a larger study with more injection conditions could present results to the contrary of the general trend of every studied combustion parameter in this study.

When considering light load, some interesting phenomenon were examined with the pilot injection, especially in its interaction with fuels of varying cetane number. From the ignition delay results, it’s clear that the combustibility of the fuel can have a large impact on the performance of the pilot injection, where inverse results were observed between the two fuels. Additional mixing, and therefore a longer mixing time, is necessary with the low CN fuel, whereas this is not necessarily true for the high CN fuel. Especially in the mass fraction burned and ignition delay results, the variations in combustion parameters due to a pilot injection of varying injection conditions at light load is clear.

Cetane number also played an integral role in all acquired results. Nowhere was this truer than in the rate of heat release results, where a dual stage combustion actually lengthened the total combustion time of the higher CN fuel. The composition of the fuel had a strong effect on all studied combustion parameters, even effecting the expected results of the multiple injection as discussed previously. Therefore, fuel choice must be a consideration for any multiple injection study.

Finally, the results of the fuel conversion efficiency seemed to be most readily effected by the rate of combustion. In the low load case, the higher CN fuel proved superior to the other fuel as the single stage combustion for each fuel was much higher in the fuel of higher combustibility. However at the medium load condition, this combustibility trait actually lengthened the speed of combustion time by creating a dual stage combustion, creating higher fuel conversion efficiencies in the lower CN fuel.

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